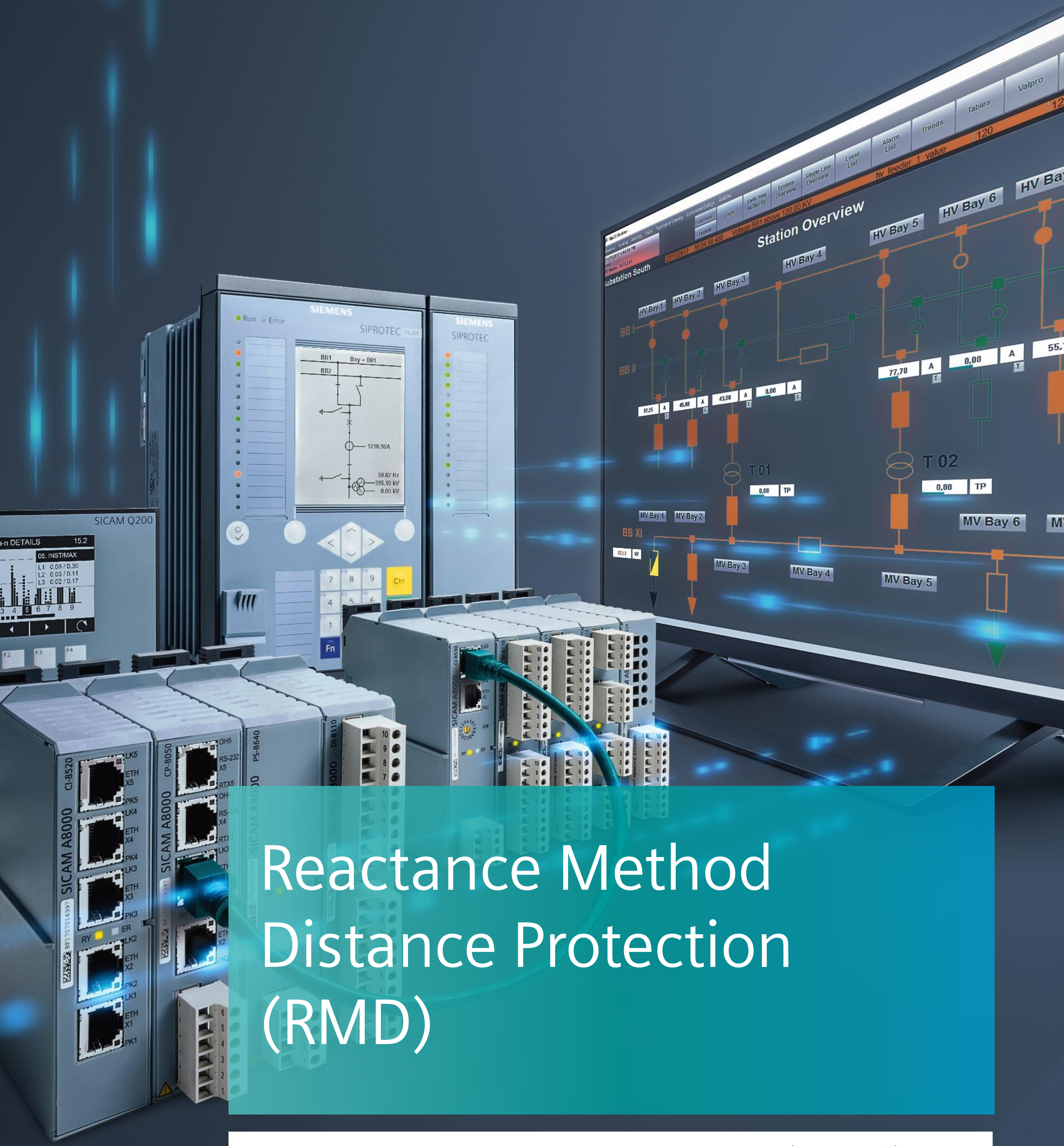
SIEMENS
Ingenuity for life



Reactance Method Distance Protection (RMD)

www.siemens.com/siprotec5

SIPROTEC 5 Application

Reactance Method Distance Protection (RMD) Compensation Factors

APN-070, Edition 1

Content

1 Reactance Method Distance Protection (RMD) Compensation Factors

1.1 Introduction

This document provides a description of the Distance protection with RMD method focusing on the load compensation and the compensation factors that can be set.

The influence of a non-homogenous source impedance is described. The description is then supported by means of an application example and simulation results based on the example application.

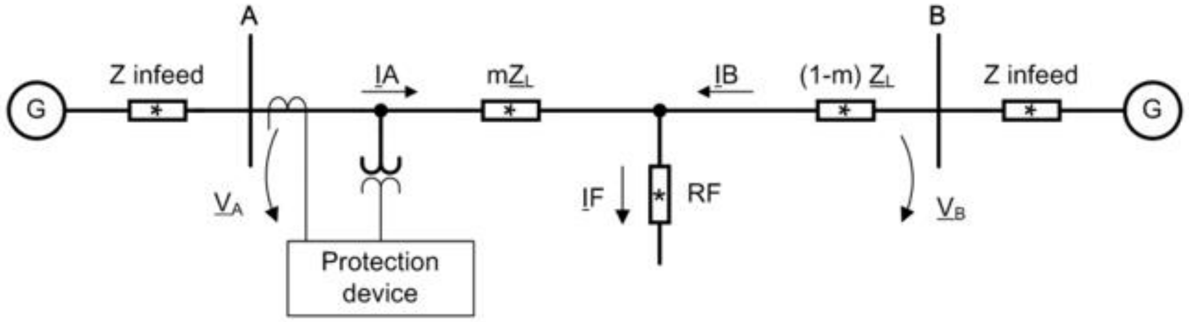
1.2 Basics

Distance protection must establish the fault location based on an impedance measurement. The loop impedance from the relay to the fault location includes the fault resistance at the fault location (RF in diagram below). As the voltage across RF depends on the fault current (IF) at the fault location, which includes the infeed from the remote end, this will affect the result of the impedance measurement.

The Reactance Method Distance Protection (RMD) includes a load compensation which eliminates the fault resistance from the loop equation. This load compensation works best in a homogenous system; such a system has the same impedance angle on both sides of the fault location. In most applications this is approximately true so that the compensation angles described here do not have to be applied.

1.2.1 Loop Equation

The generalized loop equation for the RMD is based on the following single line representation (copied from manual):

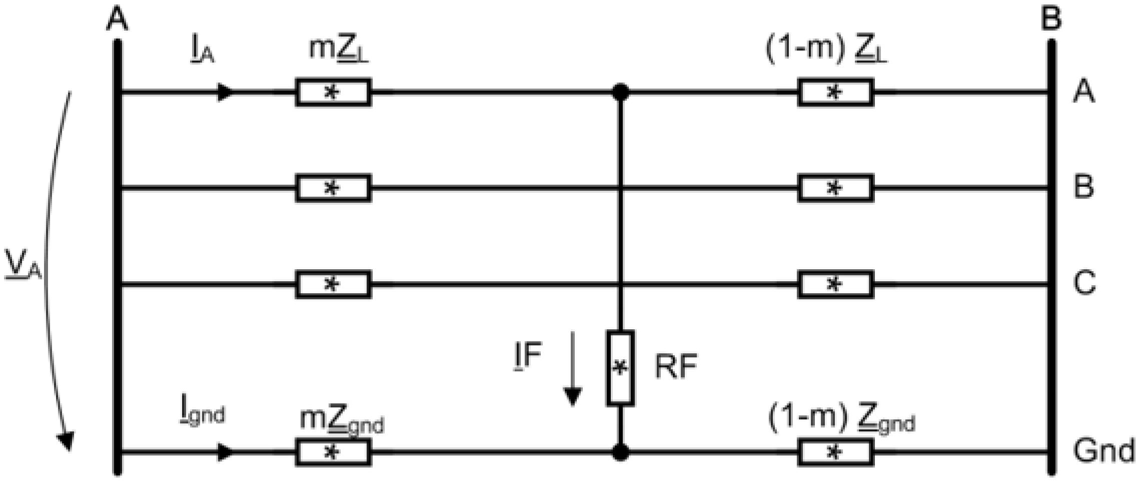


[dw ueb impedanzber, 2, en_US]

Figure 1: Line Supplied from 2 Sides (1-Pole Representation)

Based on the above single line diagram, the loop equations or the ground fault and the phase to phase faults are derived. The 3-phase faults are measured with a loop based on positive sequence values. For the 3 phase faults no compensation factors apply.

1.2.2 Ground faults



[dw_leschleife_rmd, 2, en_US]

Figure 2: Short Circuit of a Phase-to Ground Loop

And so, the ground loop equation is given as follows:

$$X = \frac{\operatorname{Im}\left\{\underline{V}_A \cdot \left[\underline{I}_{Subst\,.} \cdot e^{j\delta_{comp}}\right]^*\right\}}{\operatorname{Im}\left\{\underline{Z}_L / |Z_L| \cdot \left(\underline{I}_A - \underline{k}_0 \cdot \underline{I}_{Gnd}\right) \cdot \left[\underline{I}_{Subst\,.} \cdot e^{j\delta_{comp}}\right]^*\right\}} \cdot \sin\varphi$$

When the system is homogenous, the impedance angles on the A and B side of the fault location are the same, the factors with the compensation angles are not required; the default setting for δ_{comp} is zero ($e^0 = 1$).

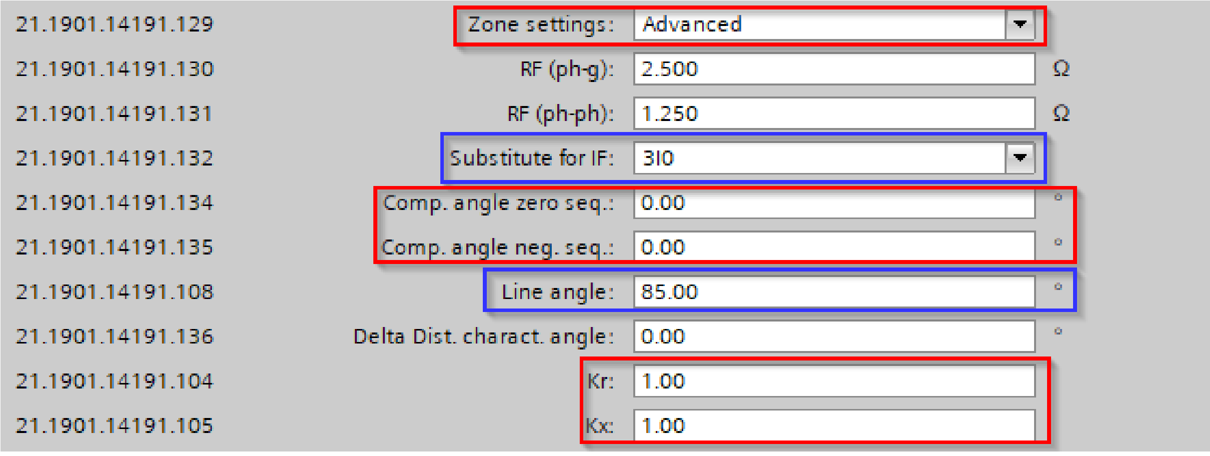
When the system is not homogenous, the source impedance at the two sides, A and B, have different impedance angles, compensation factors can be set to make allowance for the non-homogeneity.

1.2.3 Compensation factors

This above equation includes the following factors. The substitute current and the compensation angle that are specifically used in the RMD distance protection must be set for best results. The following table gives a summary and brief description of the parameters:

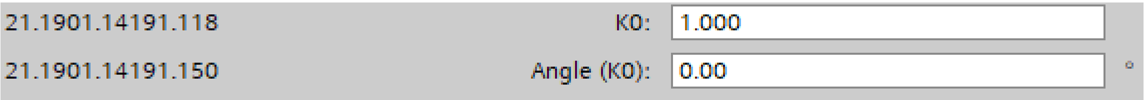
Designation	Description	Parameters, Screenshot below
$\underline{I}_{Subst}$	Current substituted for IF, for the ground loops the user can select a substitution based on either zero or negative sequence current.	:14191:131 Substitute for IF
δ_{comp}	Compensation Angle. If non homogeneity must be considered a compensation angle can be set for both zero and negative sequence.	:14191:134 Comp. angle zero seq. :14191:135 Comp. angle neg. seq
$\underline{k}_0$	Residual Compensation Factor. In DIGSI the format for entering this factor can be selected	14191:104 Kr 14191:105 Kx
φ	Line Angle	14191:108 Line Angle

The compensation factors are settable under the general settings where they apply to all zones and, optionally, each zone may be set in advanced mode with its dedicated factors. The screenshot below shows all the compensation factors as set in a zone when Zone Settings is “advanced”:



21.1901.14191.129	Zone settings:	Advanced	
21.1901.14191.130	RF (ph-g):	2.500	Ω
21.1901.14191.131	RF (ph-ph):	1.250	Ω
21.1901.14191.132	Substitute for IF:	3I0	
21.1901.14191.134	Comp. angle zero seq.:	0.00	°
21.1901.14191.135	Comp. angle neg. seq.:	0.00	°
21.1901.14191.108	Line angle:	85.00	°
21.1901.14191.136	Delta Dist. charact. angle:	0.00	°
21.1901.14191.104	Kr:	1.00	
21.1901.14191.105	Kx:	1.00	

The residual compensation factor, $\underline{k}_0$, is set by default with the two parameter Kr and Kx. The setting mode can be changed in DIGSI to enter the $\underline{k}_0$ directly with magnitude and angle:

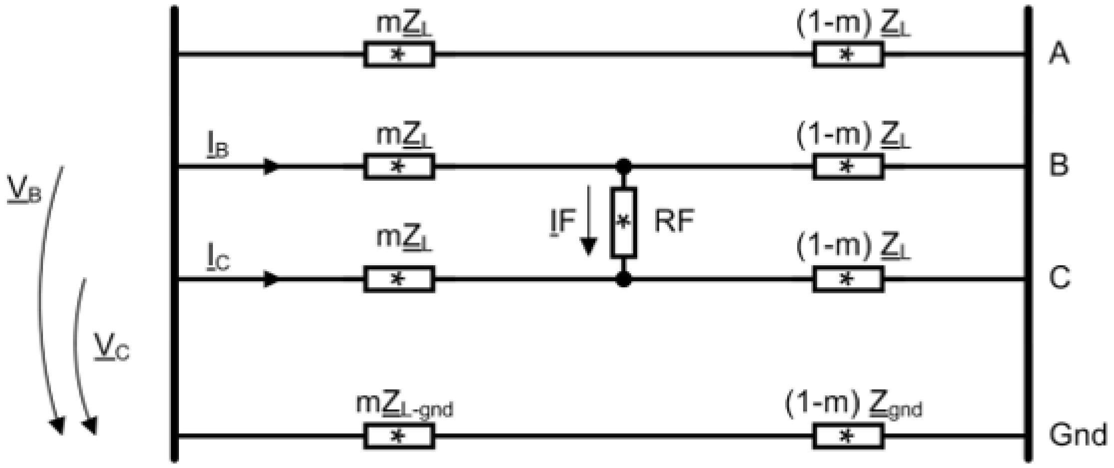


21.1901.14191.118	K0:	1.000	
21.1901.14191.150	Angle (K0):	0.00	°

Note: For the conversion from $\underline{k}_0$ to Kr and Kx the line angle setting is also considered.

1.2.4 Phase-to Phase Fault

The phase to phase loops does not have a zero-sequence component, here the substitute current is always derived from the negative sequence current. The diagram below is used to derive the loop equation.



[dw_llschleife_rmd, 3, en_US]

Figure 3: Short Circuit of a Phase-to-Phase Loop

From this the Ph-Ph loop equation is derived:

$$X = \frac{\mathrm{Im}\left\{\underline{V}_{BC} \cdot \left[\underline{I}_{\mathrm{subst}} \cdot e^{j\delta_{\mathrm{comp}}}\right]^{*}\right\}}{\mathrm{Im}\left\{\underline{Z}_{L} / |\underline{Z}_{L}| \cdot (\underline{I}_{B} - \underline{I}_{C}) \cdot \left[\underline{I}_{\mathrm{subst}} \cdot e^{j\delta_{\mathrm{comp}}}\right]^{*}\right\}} \cdot \sin\varphi$$

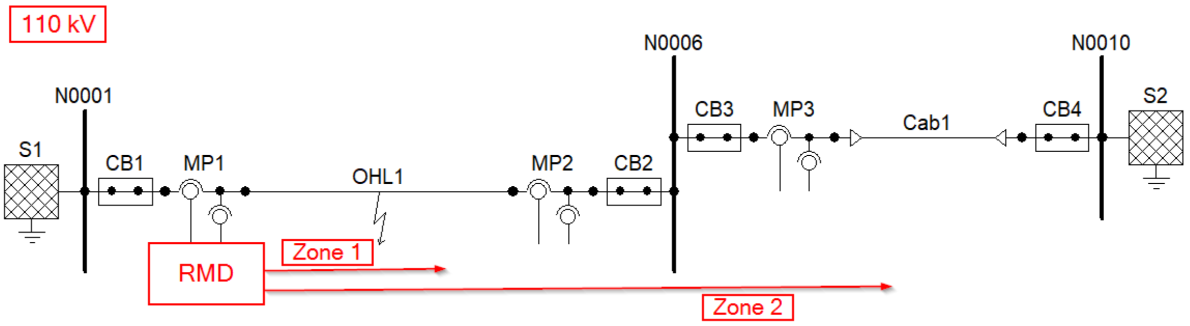
This equation includes the same compensation factors, the zero sequence factors do not apply:

Designation	Description	Parameters
I_{Subst}	Current substituted for IF	No Parameter, always based on I2
δ_{comp}	Compensation Angle	:14191:135 Comp. angle neg. seq
φ	Line Angle	14191:108 Line Angle

1.3 Example with detailed source data

To illustrate how the compensation factors can be calculated and applied an example with significantly different impedance angle at the two infeed sides is used.

The diagram below illustrates this application example. The relay that will be considered is designated as "RMD". The source behind the relay (S1) is fed by overhead lines and transformers so that it has a large impedance angle. The remote source is supplied from a cable connected network with relatively small impedance angle. A cable, Cab1, is the feeder with the smallest impedance (shortest) at the remote end and it will be used to fix the Zone 2 boundary.



For the calculation of the compensation factors the line and cable data as well as the zone reach settings are required. The table below lists the key system impedance data applicable to this example network:

Source Impedance			
	S1	S2	
Pos. Seq. R	0,132	0,522	Ohm
Pos. Seq. X	1,324	2,610	Ohm
Zero Seq. R	0,132	1,566	Ohm
Zero Seq. X	1,324	5,221	Ohm
Feeder Data	OHL1	Cab1	
Length	10,000	20,000	km
Pos. Seq. R	0,300	2,540	Ohm
Pos. Seq. X	4,100	2,460	Ohm
Zero Seq. R	1,500	7,620	Ohm
Zero Seq. X	16,400	4,920	Ohm

The RMD will be set base on the OHL impedance with 2 zones as follows:

Zone 1 = 80%

Zone 2 = 135%

1.3.1 Calculate Dr and Kx setting for Zone 1

The Zone 1 is set to underreach, the measured loop up to the zone boundary only contains the OHL impedance, and therefore the Kr and Kx setting can be calculated with the OHL1 data:

$$Z1\_Kr = \frac{1}{3} \cdot \left(\frac{R0}{R1} - 1\right)$$

$$Z1\_Kr = \frac{1}{3} \cdot \left(\frac{1{,}5}{0{,}3} - 1\right) = 1{,}33$$

$$Z1\_Kx = \frac{1}{3} \cdot \left(\frac{X0}{X1} - 1\right)$$

$$Z1\_Kx = \frac{1}{3} \cdot \left(\frac{16{,}4}{4{,}1} - 1\right) = 1$$

1.3.2 Calculate Zone 2 boundary (factor "n")

To calculate the Kr and Kx parameters for Zone 2, the total positive and zero sequence impedance between the relay and the Zone 2 boundary applies. This includes the entire OHL impedance plus a section of the cable:

How many km into Cab1 does the zone 2 reach?

$$Z2_{km\_into\_Cab1} = \left(\frac{X1_{zone2_{set}} - X1\_OHL1}{X1\_Cab1}\right) \cdot Cab1\_length$$

$$Z2_{km\_into\_Cab1} = \left(\frac{5{,}535 - 4{,}1}{2{,}54}\right) \cdot 20km = 11{,}67km$$

Based on this the "loop" impedance of Zone 2 can be calculated as follows:

<u>Zone 2 Loop imp</u>			
Pos. Seq. R	OHL1+n*Cab1	1,782	Ohm
Pos. Seq. X	Z2 setting	5,535	Ohm
Zero Seq. R	OHL1+n*Cab1	5,945	Ohm
Zero Seq. X	OHL1+n*Cab1	19,270	Ohm
km into Cab1		11,667	km
percentage reach Cab1	n	58,33%	
Zone 2	arctan (X1/R1)	72,16	°

The factor "n" derived here indicates what percentage of the cable impedance is included in the zone 2 set reach. The factor "n" will be used in several calculations below!

1.3.3 Calculate Kr and Kx setting for Zone 2

Using the loop impedances from above table, the Kr and Kx for Zone 2 can be calculated as follows:

$$Z2\_Kr = \frac{1}{3} \cdot \left(\frac{R0}{R1} - 1\right)$$

$$Z2\_Kr = \frac{1}{3} \cdot \left(\frac{5{,}945}{1{,}782} - 1\right) = 0{,}779$$

$$Z1\_Kx = \frac{1}{3} \cdot \left(\frac{X0}{X1} - 1\right)$$

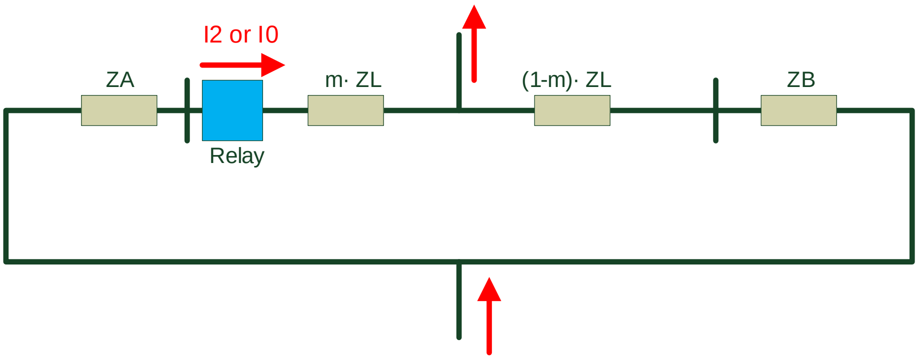
$$Z1\_Kx = \frac{1}{3} \cdot \left(\frac{19{,}27}{5{,}535} - 1\right) = 0{,}827$$

Note that the “line angle” for zone 2 must also be set as calculated in the table above (72,16°).

1.3.4 Zone 1: Compensation angels for neg. and zero sequence, δ_{comp_I2} and δ_{comp_I0}

The angle compensation factors will correct the influence of a non-homogenous loop impedance (impedance angle on source and remote side of fault location are not the same). The compensation angles are calculated at the respective zone boundaries.

In the diagram below the equivalent circuit (generalized for zero and negative sequence) for deriving the equation used to calculate the compensation angle is shown. The compensation angle equals the angle difference between the current flowing into the circuit at the bottom and the I2 (or I0) measured by the relay.



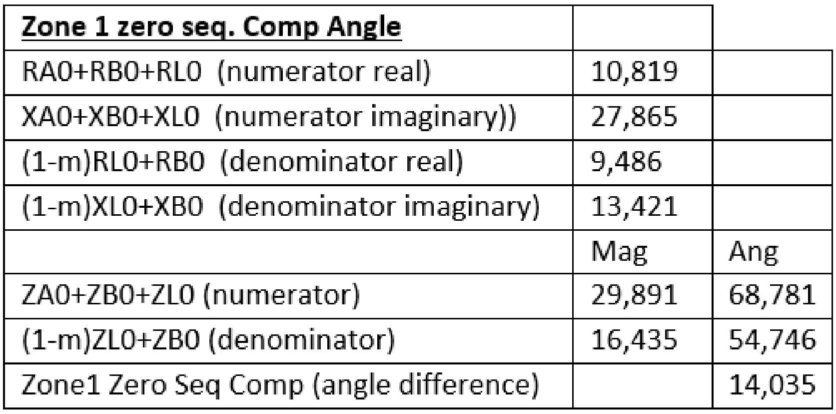
Equation for zero sequence compensation angle:

$$\delta_{comp\ ,0} = \arg\left(\frac{\underline{I}_F}{\underline{I}_{0\ Protection\quad device}}\right) = \arg\left(\frac{\underline{Z}_{A,0} + \underline{Z}_{B,0} + \underline{Z}_{L,0}}{(1-m)\underline{Z}_{L,0} + \underline{Z}_{B,0}}\right) \qquad \text{Equation 1}$$

The values that must be applied in this equation for Zone 1 are listed in the table below. Note, the source impedance, ZB, includes the Cab1 impedance in this example:

Zone 1 zero seq. Comp Angle			
RA0	S1 R0	0,15	Ohm
XA0	S1 X0	1,46	Ohm
RB0	S2 R0 + Cab1 R0	9,34	Ohm
XB0	S2 X0 + Cab1 X0	10,66	Ohm
RL0	OHL R0	1,50	Ohm
XL0	OHL X0	16,40	Ohm

With this data the numerator and denominator of the equation above can be determined:

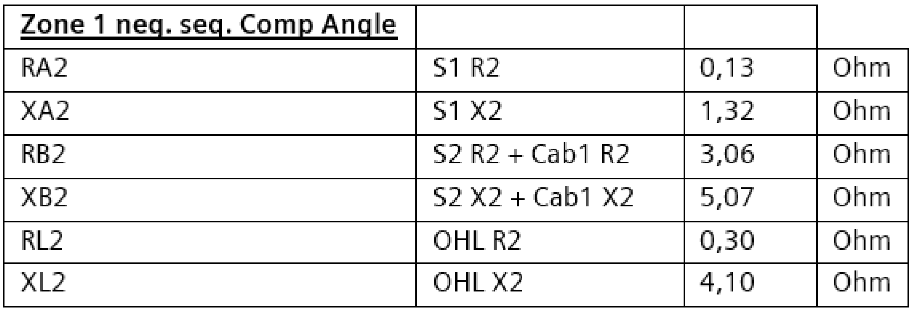


Zone 1 zero seq. Comp Angle		
RA0+RB0+RL0 (numerator real)	10,819	
XA0+XB0+XL0 (numerator imaginary))	27,865	
(1-m)RL0+RB0 (denominator real)	9,486	
(1-m)XL0+XB0 (denominator imaginary)	13,421	
	Mag	Ang
ZA0+ZB0+ZL0 (numerator)	29,891	68,781
(1-m)ZL0+ZB0 (denominator)	16,435	54,746
Zone1 Zero Seq Comp (angle difference)		14,035

The zero-sequence compensation angle $Z1\_\delta_{comp\_I0}$ for Zone 1 can then easily be calculated with the angles in above table:

$$Z1_{\delta_{comp_{I0}}} = \arg(ZA0 + ZB0 + ZL0) - \arg\big((1 - \mathrm{m})\mathrm{ZL0} + \mathrm{ZB0}\big) = 14{,}035°$$

The same procedure is applied for the negative sequence angle by using the negative sequence impedance:



Zone 1 neg. seq. Comp Angle			
RA2	S1 R2	0,13	Ohm
XA2	S1 X2	1,32	Ohm
RB2	S2 R2 + Cab1 R2	3,06	Ohm
XB2	S2 X2 + Cab1 X2	5,07	Ohm
RL2	OHL R2	0,30	Ohm
XL2	OHL X2	4,10	Ohm

With this data the numerator and denominator of the equation can be determined:

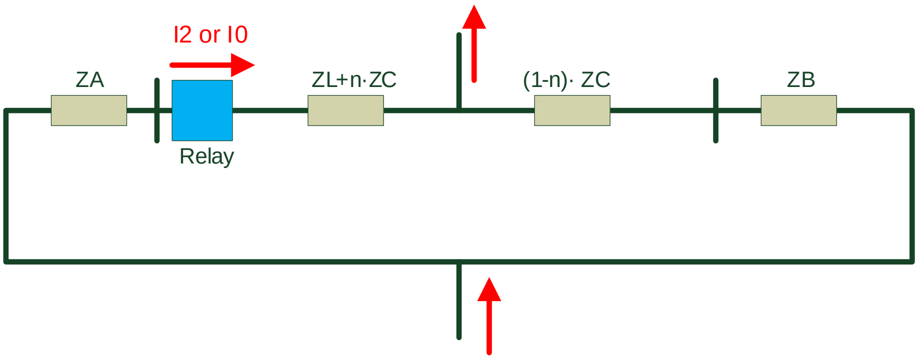
Zone 1 neg seq. Comp Angle		
RA2+RB2+RL2	3,495	
XA2+XB2+XL2	10,495	
(1-m)RL2+RB2	3,122	
(1-m)XL2+XB2	5,890	
	Mag	Ang
ZA2+ZB2+ZL2	11,061	71,583
(1-m)ZL2+ZB2	6,667	62,075
Zone1 Neg. Seq Comp		9,508

The neg-sequence compensation angle $Z1\_\delta_{comp\_I2}$ for Zone 1 can then easily be calculated with the angles in above table:

$$Z1_{\delta_{comp_{I2}}} = \arg(ZA2 + ZB2 + ZL2) - \arg\big((1 - \mathrm{m})\mathrm{ZL2} + \mathrm{ZB2}\big) = 9{,}508°$$

1.3.5 Zone 2: Compensation angels for neg. and zero sequence, δ_{comp_I2} and δ_{comp_I0}

For zone 2 the same equations apply. The impedance values must however be calculated based on the zone boundary of zone 2. In the diagram below the equivalent circuit (generalized for zero and negative sequence) for deriving the equation for calculation of the compensation angle is shown. The compensation angle equals the angle difference between the current flowing in at the bottom and the negative (or zero) sequence current measured by the relay. For the calculation the factor “n” established earlier applies. The factor “n” as calculated above (Kr and Kx setting of Zone 2), is equal to 0,583 (58,33%).



The following table shows the calculation steps (Note for the calculation the numerator is the sum of all impedances and remains the same, the denominator is the sum of the impedances on the righthand side of the fault location):

Zone 2 zero seq. Comp Angle			
RA0	S1 R0	0,15	Ohm
XA0	S1 X0	1,46	Ohm
RB0+(1-n)ZCabR0	S2 R0 + (1-n)ZCR0	4,90	Ohm
XB0+(1-n)ZCabX0	S2 X0 + (1-n)ZCX0	7,79	Ohm
RL0 + n ZCab R0	OHL R0 + n ZCR0	5,95	Ohm
XL0 + n ZCab X0	OHL X0 + n ZC X0	19,27	Ohm

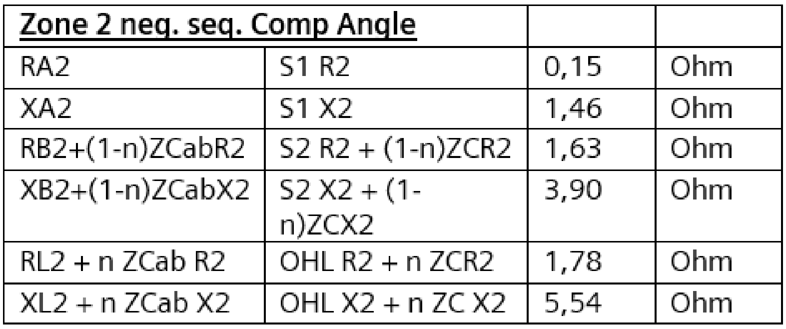
With this data the numerator and denominator of the equation can be determined:

Zone 0 zero seq. Comp Angle		
RA0+RB0+RL0	10,988	
XA0+XB0+XL0	28,520	
RB0+(1-n)ZCabR0	4,898	
XB0+(1-n)ZCabX0	7,793	
	Mag	Ang
ZA0+ZB0+ZL0	30,563	68,928
ZB0+(1-n)ZCabZ0	9,204	57,850
Zone2 Zero Seq Comp		11,078

The zero-sequence compensation angle $Z2\_\delta_{comp\_I0}$ for Zone 2 can then easily be calculated with the angles in above table:

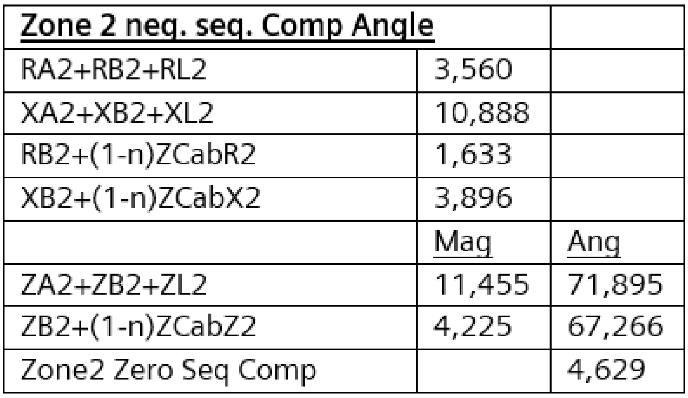
$$Z2_{\delta_{comp_{I0}}} = \arg(ZA0 + ZB0 + ZL0) - \arg\big((1 - \mathrm{n})\mathrm{Zcab0} + \mathrm{ZB0}\big) = 11{,}1°$$

The same procedure can be applied for the negative sequence angle:



Zone 2 neg. seq. Comp Angle			
RA2	S1 R2	0,15	Ohm
XA2	S1 X2	1,46	Ohm
RB2+(1-n)ZCabR2	S2 R2 + (1-n)ZCR2	1,63	Ohm
XB2+(1-n)ZCabX2	S2 X2 + (1-n)ZCX2	3,90	Ohm
RL2 + n ZCab R2	OHL R2 + n ZCR2	1,78	Ohm
XL2 + n ZCab X2	OHL X2 + n ZC X2	5,54	Ohm

The neg-sequence compensation angle $Z2\_\delta_{comp\_I2}$ for Zone 2 can then easily be calculated with the angles in above table:



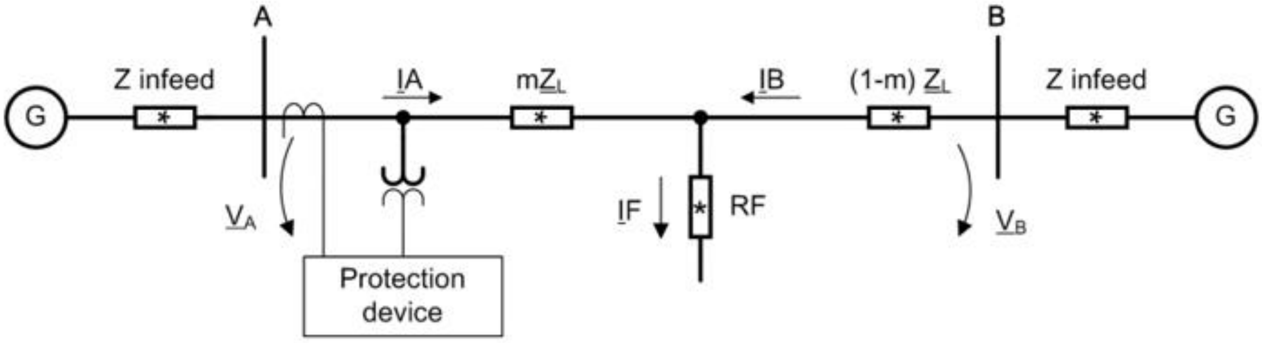
Zone 2 neg. seq. Comp Angle		
RA2+RB2+RL2	3,560	
XA2+XB2+XL2	10,888	
RB2+(1-n)ZCabR2	1,633	
XB2+(1-n)ZCabX2	3,896	
	Mag	Ang
ZA2+ZB2+ZL2	11,455	71,895
ZB2+(1-n)ZCabZ2	4,225	67,266
Zone2 Zero Seq Comp		4,629

$$Z2_{\delta_{comp_{I2}}} = \arg(ZA2 + ZB2 + ZL2) - \arg\big((1 - \mathrm{n})\mathrm{Zcab2} + \mathrm{ZB2}\big) = 4{,}6°$$

1.4 Example with limited information regarding source impedance data

What if only limited data regarding the source impedances is available. In this case the compensation angles cannot be determined exactly. Instead they can be estimated, or the default setting of 0° can be used. In many applications, using the default setting of 0° is the best compromise.

Alternatively, the available limited data may be used to adapt the compensation angle setting. The methods presented for this approach are theoretically derived. The data available in this example is limited to what is shown in the table below the single line:

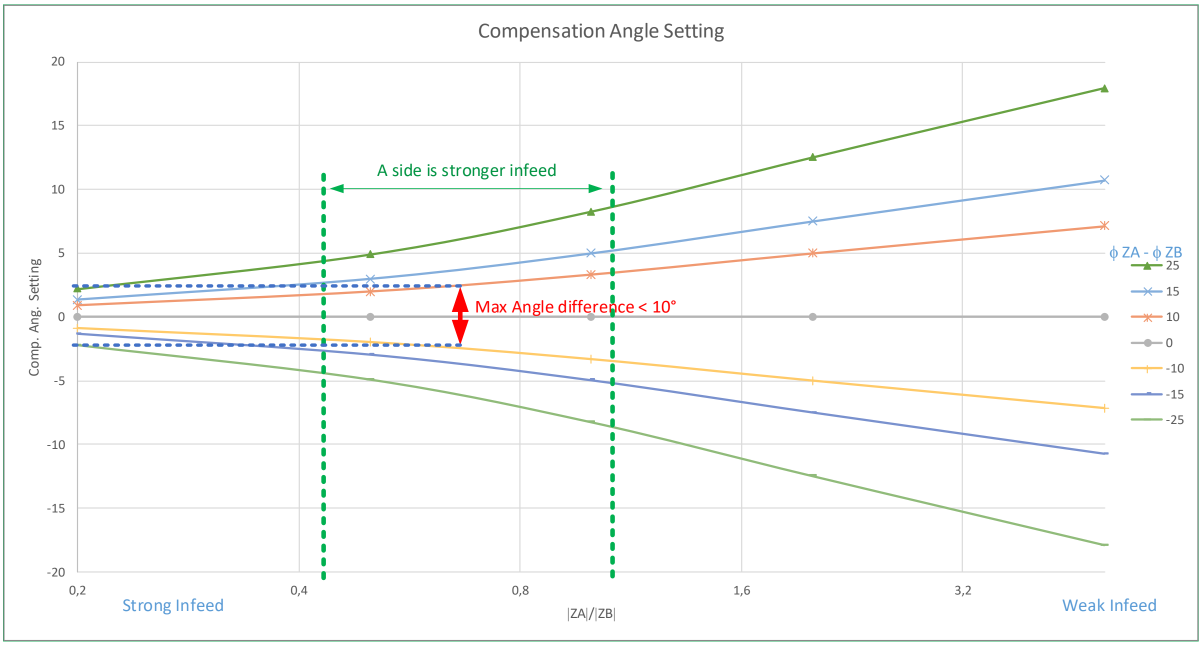


[dw ueb impedanzber, 2, en_US]

Figure 4: Line Supplied from 2 Sides (1-Pole Representation)

Description	Designation	Value		Angle Info
System voltage	VN	132 kV		
I fault 3 ph max bus A	I_3ph_maxA	12 kA		No angle information
I fault 3 ph max bus B	I_3ph_maxB	7 kA		
I fault 1 ph max bus A	I_1ph_maxA	8 kA		
I fault 1 ph max bus B	I_1ph_maxB	6 kA		
I fault 3 ph min bus A	I_3ph_minA	8 kA		No angle information
I fault 3 ph min bus B	I_3ph_minB	3 kA		
I fault 1 ph min bus A	I_1ph_minA	6 kA		
I fault 1 ph min bus B	I_1ph_minB	2 kA		
Pos. Seq. Line Imp	Z1L	RL1 = 3,6 Ohm	XL1 = 27,5 Ohm	ϕZL2 = 82.5°
Zero Seq. Line Imp	Z0L	RL0 = 17,6 Ohm	XL0 = 89,6 Ohm	ϕZL0 = 78.9°

The compensation angles cannot be calculated as in the example above, using e.g. Equation 1, due to the lack of detailed source impedance data. A good compromise is to apply boundary conditions based on typical (experience) values for source data. (this can be verified by evaluation of disturbance records).



Using the above graph, the compensation angle can be estimated. Based on the busbar short circuit currents, the side A has a negative sequence source impedance that is smaller than side B:

$$\frac{|ZA|}{|ZB|} = \frac{I_{Fault\_3ph\_B}}{I_{Fault\_3ph\_A}} = 0.25\ to\ 0.9$$

If we assume that at 132kV the impedance angle difference between the sources (and the line) is less than 10° then a setting for the negative sequence compensation angle can be derived from the diagram: approximately between -2° to +2°. Here again the option of using the default setting of 0° is mentioned because it is a good compromise. A selection based on the graph would be done using the following rule:

Comp. Factor	Applied Approximation	Reason
Zone 1 δ_{comp_I0} and δ_{comp_I2}	Smallest estimated value	Ensures that RF will always cause positive delta X
Zone 2 δ_{comp_I0} and δ_{comp_I2}	Largest estimated value	Ensures that RF will always cause negative delta X

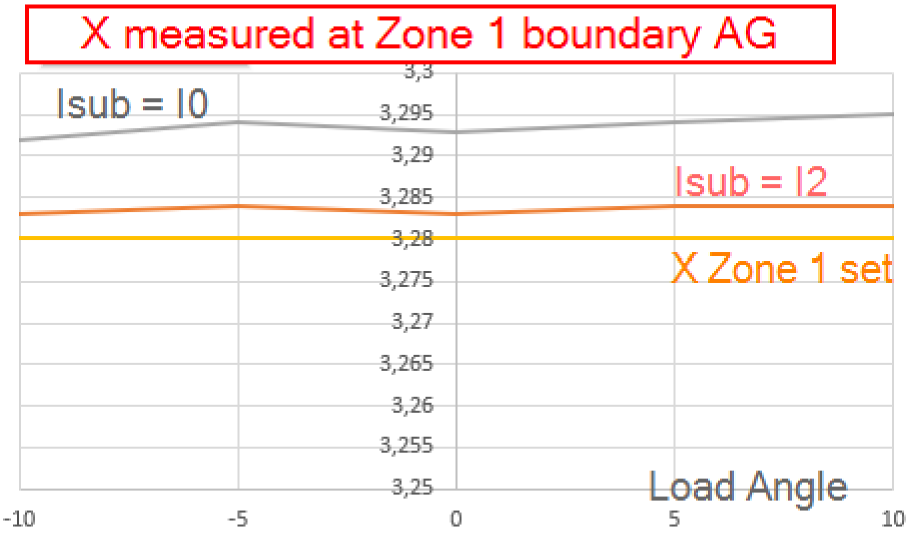
Therefore, for Zone 1 the setting of -2° is used and for Zone 2 the setting of +2° can be used.

1.5 Simulate and Check – based on example with detailed source data

With all the compensation factors set, faults are modelled to illustrate the correct operation of the settings. Faults are applied at the Zone 1 and Zone 2 boundary and the loop calculation is checked with SIGRA.

1.5.1 Tests at Zone 1 boundary

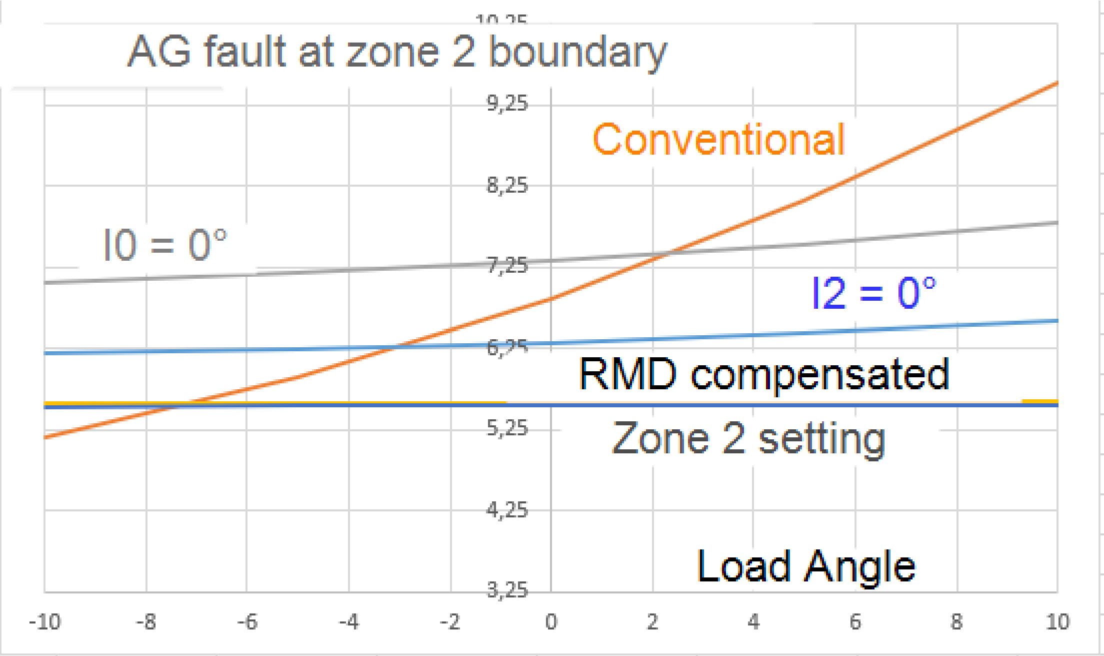
Both single phase to ground and phase to phase faults are simulated at the zone 1 boundary.



The above diagram was obtained by modelling a fault AG with 5 Ohm fault resistance at the zone 1 boundary. The maximum deviation from the set zone 1 reach was 15 mΩ (0,46%). The measurement was done by application of I0 as well as I2 as substitute; shown as separate curves in the diagram.

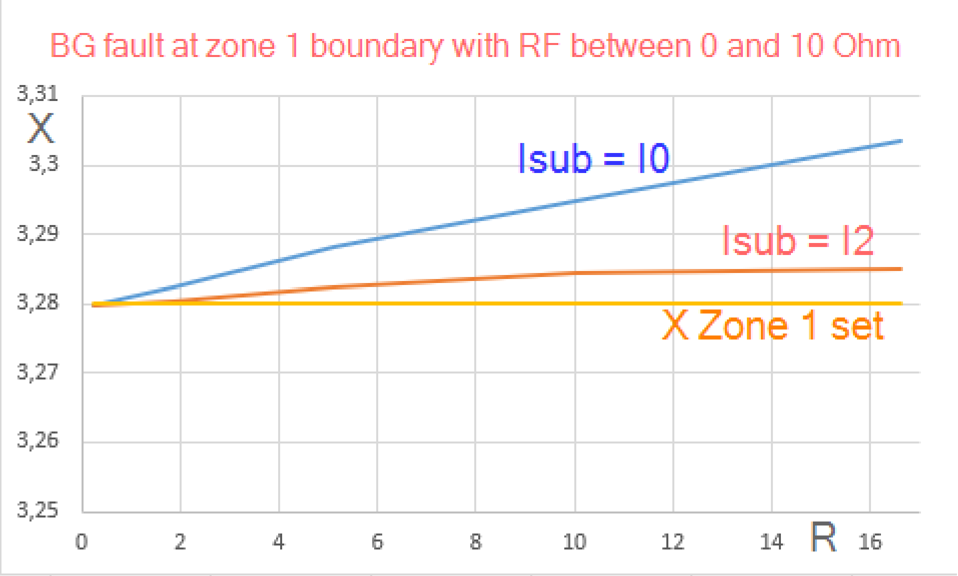
Check against un-compensated measurements

The above diagram shows very good results with the compensated measurement. To illustrate the benefit of compensation a comparison with uncompensated measurements is shown below. The RMD compensation angles are left on default (δ_{comp} =0) and the conventional distance protection without load compensation are used in the comparison below.



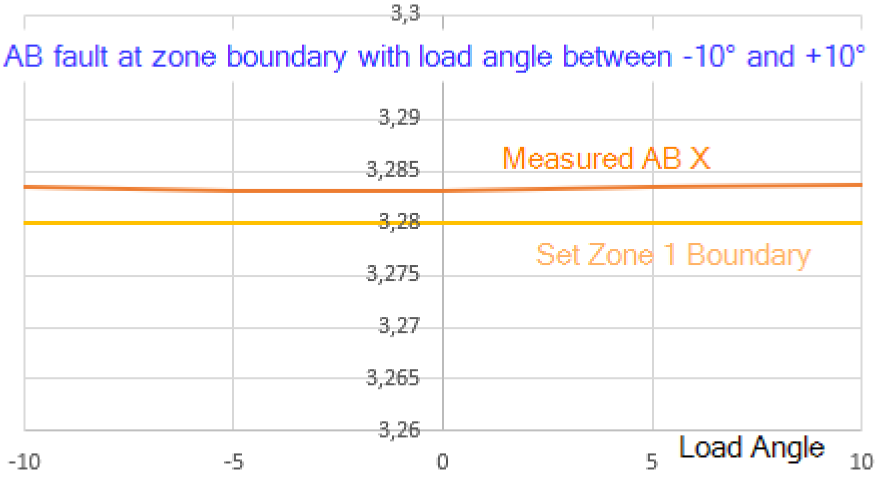
This comparison shows that the uncompensated measurement has significant deviation compared to the compensated measurement.

The conventional impedance protection has a load angle dependency that is superimposed on the measuring error due to non-homogeneity. At no load (load angle = 0) it has a result similar to RMD without compensation angles. With load export it measures a smaller impedance and with load import a larger impedance.



The above diagram was obtained by modelling a fault BG with fault resistance increasing from 0 Ohm to 10 Ohm. The load angle was -10° . The maximum deviation from the set zone 1 reach was 23 mΩ (0,71%). The measurement was done by application of I0 as well as I2 as substitute; shown as separate curves in the diagram.

Finally, a set of tests are done with Ph-Ph faults:

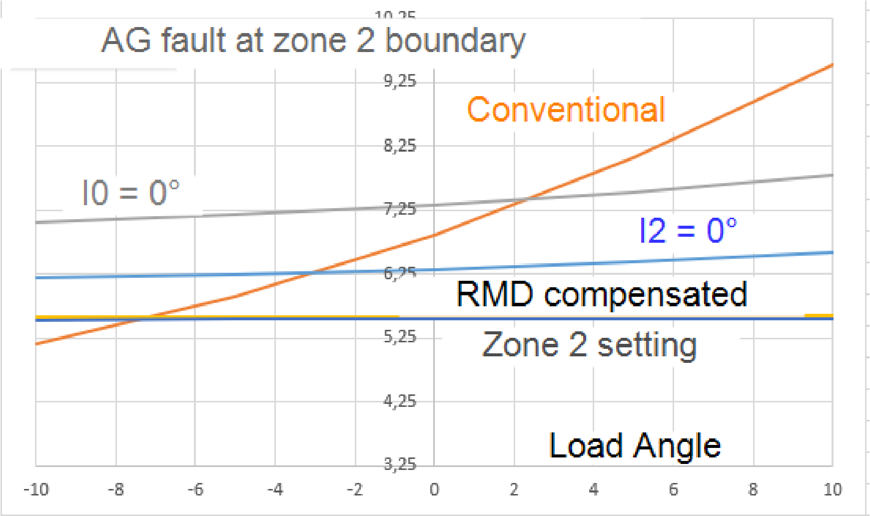


The phase to phase faults are also measured with negligible deviation from the expected fault reactance.

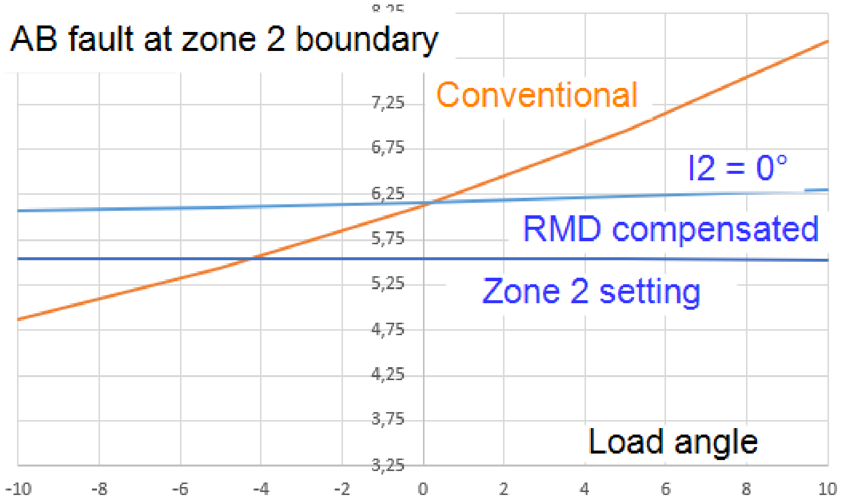
1.5.2 Tests at Zone 2 boundary

Both single phase to ground and phase to phase faults are simulated at the zone 2 boundary to check if the calculated compensation factors are correct.

The diagram below illustrates the effectiveness of the compensation angles.



The uncompensated RMD (I0 = 0° and I2 = 0°) show a relatively constant positive error and the conventional distance protection has a load angle dependent deviation, similar to what was observed at the zone 1 boundary. The compensated RMD has a result with insignificant deviation from the set boundary.



The tests with AB faults at the zone 2 boundary confirm the results.

1.6 Conclusion

The correct operation is highly dependent on the correct application of the residual or zero-sequence compensation factor. It is not explicitly indicated in the relay manual and personnel will need to find this out. This document should support the personal applying the RMD method focusing on the load compensation and the compensation factors that can be set and supports for selecting the most suitable model for testing.

It should also support the personnel who set relays and those who test them for a better understanding of the methods of residual compensation, how the resistive reach is set and affected by the compensation and how the relay characteristics are modeled.

Published by
Siemens AG

Smart Infrastructure
Digital Grid
Humboldtstrasse 59

90459 Nuremberg, Germany

www.siemens.com/siprotec

For more information, please
contact our Customer Support
Center.

Tel.: +49 180 524 70 00
Fax: +49 180 524 24 71
(Charges depending on provider)

Customer Support: www.siemens.com/csc

For the U.S. published by
Siemens Industry Inc.

100 Technology Drive
Alpharetta, GA 30005
United States